Space-Time Focusing Transmission in Ultra-wideband Cooperative Relay Networks

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***Abstract*— Space-time focusing transmission is a generalized form of beamforming in ultra-wideband (UWB) systems by exploiting the unique feature of UWB signals. It can obtain energy gain and can reduce interference to coexisting users, thus can extend the distance and increase the capacity of UWB communications. Cooperative relay can further extend the coverage of UWB systems. In this paper, we first propose ZF and MMSE prefiltering algorithms for space-time focusing transmission, and then propose a space-time focusing based cooperative relay scheme. The throughputs of broadcast mode and multiple access mode in the relay networks are derived, while their dependency on various system parameters is obtained. Numerical results show how many cooperative nodes are necessary to maximize the network throughput, and when the proposed prefiltering algorithms perform well.**

I. INTRODUCTION

Impulse radio ultra-wideband (IR-UWB) technology is promising in military communication systems and wireless sensor networks due to its superior capability for providing security and coexistence. However, more widespread applications to longer range communications are restricted by the hard constraint of the power spectrum density imposed on UWB systems.

UWB systems are different from narrow-band systems in its impulse nature and strict transmit power constraint. The impulse signal provides fine temporal and spatial resolvability, which can be exploited for designing the space-time focusing transmission [1], [2]. The focused signal can only be received at specific locations and times. This leads to very low leakage interference to coexisting users.

As a generalized form of beamforming, space-time focusing can improve the link performance in two ways. For a given transmission power, the transmission range can be extended by focusing the signal to a far away node. For a given transmission range, the transmission power can be reduced. As a result, the interference to other coexisting users will decrease and the network capacity will increase.

The well studied time-reversal (TR) technique [3]–[8] can be applied for space-time focusing transmission in UWB systems. In the transmit side, the time-reversed and phase-conjugated channel response is used as a prefilter, where the physical channel serves as a temporal and spatial matched filter (MF). However, the output SINR of TR scheme is limited by the imperfect auto-correlation and cross-correlation characteristics of UWB channels. To improve the space-time focusing performance, we will propose in this paper advanced prefiltering algorithms based on zero-forcing (ZF) and minimum-mean-square-error (MMSE) criterions.

Even when we use advanced prefiltering algorithms for space-time focusing transmission, point-to-point link can only reach a limited distance. To further extend the coverage, we design a cooperative relay network where each node transmits with the space-time focusing prefiltering. Considering that the source information can not arrive at the destination directly, we study the parallel relay network, which consists of a broadcast (BC) mode and a multiple-access (MA) mode transmissions [9]–[11].

Since joint synchronization among relay nodes is hard to be implemented, especially in UWB systems, joint space-time energy focusing is impossible if we use the beamforming concept straightforwardly. It is well known that in energy-limited systems, the mutual information accumulation is the same as the energy accumulation due to the linear growth of the capacity on the power [12]. Thus we propose to transmit independent streams from different relays to the destination. We can obtain the same throughput with the joint energy focusing scheme when the focused pulses from different relays do no collide.

In order to understand the potential of space-time focusing transmission in UWB systems, we study the performance of TR and the two proposed prefiltering algorithms in the cooperative relay network with simple but typical topologies. The impact of relay number and channel delay spread is analyzed, and the collision probability is obtained in MA mode transmissions.

The rest of the paper is organized as follows. Section II and III describes the proposed space-time focusing prefiltering algorithms and the cooperative relay scheme. Section IV analyzes the network throughput and the optimal cooperative relay number. Numerical results are given in section V to compare the TR prefiltering with the ZF and MMSE prefilterings in various scenarios, and conclusions are provided in the last section.

II. SPACE-TIME FOCUSING TRANSMISSION

In free space, we must use multiple antennas for space-time focusing transmission [13]–[15]. In multipath channels, however, one antenna is enough since the delays of multiple transmitted pulses can be controlled to arrive at the receiver at the same time.

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We can use prefiltering to adjust the transmit time and amplitude of the pulses. The simplest space-time focusing prefiltering scheme is time-reversal, but its performance is degraded by the imperfect auto-correlation and cross-correlation characteristics of UWB channels. It is well known that ZF and MMSE criterions are better than MF criterion in terms of maximizing the signal to interference and noise ratio (SINR). In the sequel, we will design the prefilters based on these two criterions for BC and MA modes transmission (these modes will be described in more details in Section III).

In IR-UWB multiuser systems, the transmitted signal of the k-th user using pulse amplitude modulation (PAM) before prefiltering is

$$s^{(k)}(t) = \sum_{n=0}^{N_s-1} x_n^{(k)} p(t - nT_s), \tag{1}$$

where N_s is the symbol number in a packet, $x_n^{(k)}$ is the modulated amplitude of the n-th transmitted symbol for the k-th user, $p(t)$ is the UWB pulse with width T_p, T_s is the symbol duration, and $T_s = NT_p$. For the brevity of descriptions, spreading is not considered, and the energy of each symbol is normalized.

In practical UWB channels, the arrival time of the multipath components is not equally spaced. Nevertheless, after the pulse matched filter and sampling, the equivalent channel model is equally spaced [16], while some channel coefficients are weak or even zero. Assume that the channel response of the kth user is

$$h^{(k)}(t) = \sum_{l=0}^{L_c^{(k)}-1} h_l^{(k)} \delta(t - lT_p), \tag{2}$$

where $L_c^{(k)}$ is the number of resolvable paths in the kth link, $h_l^{(k)}$ is the channel fading coefficient, $\max_k\{L_c^{(k)}\} = L$.

Employing prefilter with coefficients $g_l^{(k)}$ and length $L_p^{(k)}$, the transmitted signal will be

$$\tilde{s}^{(k)}(t) = \sum_{n=0}^{N_s-1} x_n^{(k)} \sum_{l=0}^{L_p^{(k)}-1} g_l^{(k)} p(t - nT_s - lT_p). \tag{3}$$

When TR technique is considered, $g_l^{(k)} = h^{*(k)}(L_c^{(k)} - l)$, no matter in BC or in MA modes. When $L_c^{(k)} > N$, *i.e.*, ISI exists, the prefilter length $L_p^{(k)}$ will also be larger than N.

To suppress the intersymbol interference (ISI) and multiuser interference (MUI), ZF or MMSE criterion can be used to design the prefilter. Then the focusing peak in temporal and the focusing area in spatial will be sharper.

In BC modes, all the K users are synchronous, the transmitted signal is a summation of K prefiltered signals,

$$\tilde{s}(t) = \sum_{k=0}^{K-1} \tilde{s}^{(k)}(t). \tag{4}$$

The received signal of the kth user is

$$r^{(k)}(t) = \tilde{s}(t) * h^{(k)}(t) + z(t), \tag{5}$$

where the operator '$*$' denotes linear convolution, and $z(t)$ is the additive white Gaussian noise (AWGN) with zero mean and power spectrum density N_0.

The received signal is only sampled at the focused peak positions,

$$y_n^{(k)} = r^{(k)}(t) * p(t)|_{t=nT_s}. \tag{6}$$

Define the samples at time nT_s of all K users as a vector $\boldsymbol{y} = [y_n^{(1)}, y_n^{(2)}, \cdots, y_n^{(K)}]^T$. Then we can rewritten the discrete received signal as

$$\boldsymbol{y} = \boldsymbol{H}'\boldsymbol{G}\boldsymbol{x} + \boldsymbol{z}, \tag{7}$$

where $\boldsymbol{H}$ is the channel matrix, the symbol $(\cdot)'$ denotes matrix conjugate transpose, $\boldsymbol{G}$ is the prefiltering matrix, $\boldsymbol{x}$ is the transmitted amplitude vector, and $\boldsymbol{z}$ is the noise vector. The channel matrix is composed by each user's channel vector $\boldsymbol{h}^{(k)}$, *i.e.*,

$$\boldsymbol{H} = [\boldsymbol{h}^{(1)}, \boldsymbol{h}^{(2)}, \cdots, \boldsymbol{h}^{(K)}],$$

where,

$$\boldsymbol{h}^{(k)} = [h_0^{(k)}, h_1^{(k)}, \cdots, h_{L-1}^{(k)}]^T.$$

The expressions of the prefiltering matrix and the transmitted amplitude vector are, however, depended on whether ISI exists. When there is no ISI,

$$\begin{aligned} \boldsymbol{x} &= [x_n^{(1)}, x_n^{(2)}, \cdots, x_n^{(K)}]^T, \\ \boldsymbol{G} &= [\boldsymbol{g}^{(1)}, \boldsymbol{g}^{(2)}, \cdots, \boldsymbol{g}^{(K)}], \\ \boldsymbol{g}^{(k)} &= [g_0^{(k)}, g_1^{(k)}, \cdots, g_{L-1}^{(k)}]^T. \end{aligned}$$

Using the reciprocity of wireless channels, the transmitter can obtain the channel matrix $\boldsymbol{H}$. Then the prefilter matrix can be obtained with ZF and MMSE criterions respectively as

$$\boldsymbol{G}_{\text{ZF}} = \boldsymbol{H}(\boldsymbol{H}'\boldsymbol{H})^{-1}, \tag{8}$$

$$\boldsymbol{G}_{\text{MMSE}} = \boldsymbol{H}(\boldsymbol{H}'\boldsymbol{H} + \sigma^2\boldsymbol{I})^{-1}. \tag{9}$$

When there is ISI, *i.e.*, $L/N = M > 1$, the consecutive transmitted symbols $x_{n-M+1}^{(k)}$ to $x_{n+M-1}^{(k)}$ will all have contributions to the received symbol $y_n^{(k)}$, then

$$\begin{aligned} \boldsymbol{x} &= [\boldsymbol{a}_n^{(1)}, \boldsymbol{a}_n^{(2)}, \cdots, \boldsymbol{a}_n^{(K)}]^T, \\ \boldsymbol{a}_n^{(k)} &= [x_{n-M+1}^{(k)}, \cdots, x_n^{(k)}, \cdots, x_{n+M-1}^{(k)}], \\ \boldsymbol{G} &= [\boldsymbol{P}^{(1)}, \boldsymbol{P}^{(2)}, \cdots, \boldsymbol{P}^{(K)}], \\ \boldsymbol{P}^{(k)} &= [\boldsymbol{g}_{-M+1}^{(k)}, \cdots, \boldsymbol{g}_0^{(k)}, \cdots, \boldsymbol{g}_{M-1}^{(k)}]^T, \end{aligned}$$

where $\boldsymbol{g}_m^{(k)}$ is a vector down-shifted from $\boldsymbol{g}^k$ by mN elements, and the upper mN elements are filled by zeros. Similarly, $\boldsymbol{g}_{-m}^{(k)}$ is a vector up-shifted from $\boldsymbol{g}^k$ by mN elements, and the lower mN elements are filled by zeros. The relative shifting between adjacent $\boldsymbol{g}_m^{(k)}$ is N elements.

In this case, $\boldsymbol{G}$ can not be obtained from (8) or (9) directly, since its dimension is larger than $\boldsymbol{H}$'s. Considering that there exists shifting relations among the columns of $\boldsymbol{G}$, we can solve this problem by using a equivalence formula. Since both the prefilter and the channel can serve as linear filters, the received signal will be identical if we swap the two matrices, that means

$$\boldsymbol{H}'\boldsymbol{G} = \tilde{\boldsymbol{G}}'\tilde{\boldsymbol{H}}, \tag{10}$$

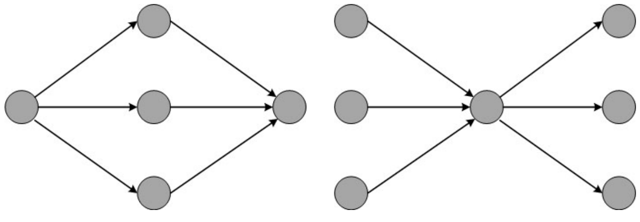

Fig. 1. (a) Single-source multiple-relay cooperative network topology. (b) Multiple-source single-relay cooperative network topology.

where

$$\begin{aligned}\tilde{\boldsymbol{G}} &= [\boldsymbol{g}^{(1)}, \boldsymbol{g}^{(2)}, \cdots, \boldsymbol{g}^{(K)}],\\ \tilde{\boldsymbol{H}} &= [\boldsymbol{Q}^{(1)}, \boldsymbol{Q}^{(2)}, \cdots, \boldsymbol{Q}^{(K)}],\\ \boldsymbol{Q}^{(k)} &= [\boldsymbol{h}^{(k)}_{-M+1}, \cdots, \boldsymbol{h}^{(k)}_{0}, \cdots, \boldsymbol{h}^{(k)}_{M-1}]^T.\end{aligned}$$

$\tilde{\boldsymbol{G}}$ can then be obtained from $\tilde{\boldsymbol{H}}$ with ZF and MMSE criterions, and the prefilter coefficients of each user are the columns of $\tilde{\boldsymbol{G}}$.

In MA modes, each user transmit its own prefiltered signal without joint synchronization. The received signal is a summation of all K signals each with a random delay τ_k,

$$r(t) = \sum_{k=0}^{K-1} \tilde{s}^{(k)}(t-\tau_k) * h^{(k)}(t) + z(t). \tag{11}$$

To demodulate the information of all K users, we need K samples in one symbol duration. The sample for the kth user is

$$y_n^{(k)} = r(t) * p(t)|_{t=nT_s+\tau_k}. \tag{12}$$

It is different in designing the prefilter in MA modes from that in BC modes. In BC modes, we assume that the transmitter knows the data and channel information of all K users, thus the pre-MUD can be used. In MA modes, however, each transmitter only knows its own data and channel information, thus the pre-EQU is applied. The pre-EQU for each transmitter can be designed as conventional channel-inverse ZF or MMSE pre-equalizers. Since there is no joint synchronization, the focused peak of other links may appear at any time, thus all the sidelobes should be suppressed.

III. COOPERATIVE RELAY UWB NETWORKS

To further extend the coverage of UWB communications, we consider to use parallel relay networks where each node transmits with prefiltering. As shown in Fig. 1(a), the source information can not arrive the destination directly. The developed schemes and analysis results can be easily extended to other network topologies, such as the multiple-source single-relay topology, as shown in Fig. 1(b).

In parallel relay networks, a source node tries to transmit information to a destination node through multiple relays. There are two stages in this transmission procedure. The first stage is the BC mode transmission, where the source node distributes information to the relays. The second stage is the MA mode transmission, where multiple relays transmit their information to the destination.

There has been intensive studies on the relaying schemes in narrow-band systems, such as *amplify-and-forward*, *decode-and-forward*, distributed space-time coding, and distributed beamforming (DBF) [17]–[19], *etc.* However, UWB systems differ in nature from the narrow-band systems since they are *impulse-based* and *power-limited*.

UWB systems can resolve a large number of multipath components in densely scattered channels, therefore can obtain abundant diversity gain from each link. As a consequence, we do not need to combine the multiple links to obtain more diversity gain, what we require is the energy gain. Space-time focusing transmission can provide such an energy gain in each link.

To realize the joint space-time focusing in an analogous way of DBF, joint synchronization among the multiple relay nodes is necessary. However, joint synchronization is hard to be implemented in distributive networks, especially in IR-UWB relay networks.

Noting that in energy-limited systems the mutual information accumulation is the same as the energy accumulation, we can transmit independent streams from different relays to the destination without the need of joint synchronization. The accumulated throughput will be the same with the joint energy focusing scheme when the randomly arrived signals do not collide at the destination, thanks to the impulse nature of the signals.

In BC mode, the source transmits independent streams to different relays using pre-MUD algorithms. In MA mode, each relay forwards its stream to the destination employing pre-EQU algorithms. In this way, the receiver in relays and in the destination are very simple, where only sampling and decision are required.

With the growing of the number of relays, there will be increased interference among BC links and increased collision among MA links. To avoid complicated retransmission mechanisms in the network, an advanced error control scheme, rateless code [20]–[24], can be used. With the help of the rateless code, the relays and destination can directly discard the error packets, and can recover the source information after collecting enough number of packets without considering their arrival sequence.

IV. PERFORMANCE ANALYSIS

In this section, we will analyze the throughput of the proposed UWB cooperative relay network. Its dependency on system parameters, such as relay number, multipath delay, and pulse repetition frequency (PRF), will be studied.

A. Broadcast Mode

In BC mode, the same transmit power P_t are used for all users. We assume that the signal of all users have the same PRF, and the received power of the desired user at a given node is P_r.

We first study the received SINR when TR prefiltering is used. Assume that every multipath component is a zero mean independent random variable with average power $\Delta_i(\tau)$, where subscript i represents the ith user. When $\tau_{\max} < T_f$, *i.e.*, no ISI exists, the interference signal in the ith user from other users is

$$I(t) = \sum_{k=0,k\neq i}^{K-1} \sqrt{P_r} h_k^*(-t) * h_i(t). \tag{13}$$

Since the signals are synchronous in BC mode, the desired focusing peak is only impacted by the interference at that time. The peak is focused at $t = 0$, therefore the average interference power is the mean square of $I(0)$, *i.e.*,

$$\begin{aligned} P_I &= E\left\{|I(0)|^2\right\} \\ &= P_r E\left\{\left|\sum_{k=0,k\neq i}^{K-1}\sum_{l=0}^{L-1} h_k^*(l)h_i(l)\right|^2\right\} \\ &= P_r \sum_{k=0,k\neq i}^{K-1}\sum_{l=0}^{L-1} E\{|h_k(l)|^2\}E\{|h_i(l)|^2\} \\ &= P_r \sum_{k=0,k\neq i}^{K-1}\sum_{l=0}^{L-1} \Delta_k(l)\Delta_i(l). \end{aligned} \tag{14}$$

In the derivation, we have used the discrete form expression of the UWB channel response, where $L = \tau_{\max}/T_p$ is the number of resolvable paths.

To gain more insight, we consider a special case that the channel has flat power delay profile and its total power is normalized, then $\Delta_k(l) = \frac{1}{L}$ and

$$P_I = \frac{K-1}{L}P_r = \alpha P_r, \tag{15}$$

where $\alpha = (K-1)/L$, it will converge to K/L when both K and L approach infinity.

The multipath components can be viewed as random spreading sequences when the channel power delay profile is flat, where L reflects the *spreading gain*, α reflects the *network load.* In general cases, UWB channel power delay profiles are not flat, and the multipath channel length L may not exactly reflect the spreading gain. However, some approximations can be made to evaluate the impact of multipath channel length. For example, the length of RMS delay spread can be used to reflect the spreading gain. Due to the lack of space, we skip the detailed analysis in this paper.

The output SINR at BC mode is

$$\beta = \frac{P_r}{\sigma^2 + P_I} = \frac{P_r}{\sigma^2 + \alpha P_r}, \tag{16}$$

where $\sigma^2 = R_b N_0$. Given a required SINR β^*, the achievable data rate can be calculated as

$$R_b = \frac{P_r}{N_0}\left(\frac{1}{\beta^*} - \alpha\right). \tag{17}$$

It shows that if TR prefiltering is used, $\alpha < \frac{1}{\beta^*}$ is required, *i.e.*, the user number K should be less than $\frac{L}{\beta^*} + 1$.

When there exists ISI, *i.e.*, $\tau_{\max} > T_f$, we can analyze the output SINR in an analogous way by regarding the ISI as a special kind of MUI. The number of equivalent "interference users" is then $\frac{\tau_{\max}}{T_f}(K-1)$, and the interference power becomes

$$P_I = R_f \tau_{\max} \alpha P_r. \tag{18}$$

The result shown in (16) is the same as the average output SINR of the MF receiver developed in random spreading CDMA systems [25], where the asymptotic expressions of the output SINR of ZF and MMSE multiuser detectors are also developed. Without considering the transmit power constraints, the received SINR using a ZF or MMSE prefilter in the transmitter and that using a ZF or MMSE detector in the receiver should be equal. Although the asymptotic results only converge when both the spreading sequence length and the user number approach infinity [25], these results are still of practical significance for providing guidelines in system design.

The average output SINR of the ZF pre-MUD is [25]

$$\beta = \begin{cases} \frac{P_r(1-\alpha)}{\sigma^2}, & \alpha < 1 \\ 0, & \alpha \geq 1 \end{cases}, \tag{19}$$

where the impact of channel fading has been averaged. In the same way, given β^*, we can obtain the achievable data rate R_b when ZF prefilter is used, *i.e.*,

$$R_b = \frac{P_r}{N_0}\left(\frac{1-\alpha}{\beta^*}\right). \tag{20}$$

The average output SINR of the MMSE pre-MUD of the ith user is [25]

$$\beta = \frac{P_{r,i}}{\sigma^2 + \frac{1}{L}\sum_{k=1,k\neq i}^{K} I(P_{r,k}, P_{r,i}, \beta)}, \tag{21}$$

where

$$I(P_{r,k}, P_{r,i}, \beta) = \frac{P_{r,k}P_{r,i}}{P_{r,i} + P_{r,k}\beta}, \tag{22}$$

$P_{r,i}$ and $P_{r,k}$ are the received power of the ith and kth user. In BC modes, they are identical.

The achievable data rate can then be obtained as

$$R_b = \frac{P_r}{N_0}\left(\frac{1}{\beta^*} - \frac{\alpha}{1+\beta^*}\right). \tag{23}$$

The throughput of the BC mode is the sum rate of K users, *i.e.*,

$$R_{t,\mathrm{BC}} = K R_b. \tag{24}$$

From the expression shown in (17), (20), and (23), we know that increasing the user number will reduce the single user data rate due to the increased multiuser interference. Meanwhile, more simultaneous transmission links will increase the network throughput given the single link transmission rate. Therefore, there should be an optimal values of the link number.

Since R_b is a linear function of α, and $\alpha = (K-1)/L$, (24) is a quadratic function of K, we can obtain its maximal value at the point where its first derivative equals zero. Thus we can obtain the optimal relay number K_{opt} with three kinds of prefilters as follows,

$$K_{\text{opt}} = \begin{cases} [\frac{L}{2\beta^*}], & \text{for TR prefilter} \\ [\frac{L}{2}], & \text{for ZF prefilter} \\ [\frac{L(1+\beta^*)}{2\beta^*}], & \text{for MMSE prefilter} \end{cases}, \tag{25}$$

where $[\cdot]$ denotes round operator.

B. Multiple-Access Mode

In MA modes, the transmit power of each node is assumed as the same, but the received power may be very different because of the propagation distance. In addition to the interference power, the collision among the focused peaks from multiple users will also affect the throughput.

We first assume that no collision happens. Then the received SINR with the TR prefilter is

$$\beta_i = \frac{P_{r,i}}{\sigma^2 + \frac{1}{L}\sum_{k=1,k\neq i}^{K} P_{r,k}}, \tag{26}$$

and R_b can be calculated as before. When the ZF or MMSE pre-EQU is used, the sidelobe will be very low and the interference from other users can be ignored, so that

$$\beta_i = \frac{P_{r,i}}{\sigma^2}. \tag{27}$$

In MA modes, pulse collision is one of the critical factors that degrade the throughput. To get a concise expression of the collision probability, we need an idealized assumption that all pulses arrive in uniform delay and in discrete interval, i.e., it must fall in one of the $N = T_f/T_p$ time slots and can not span across two time slots. The collision probability can be derived as

$$p_c = 1 - \left(\frac{N-1}{N}\right)^{K-1}. \tag{28}$$

The proof comes from a classic probability problem. Put K balls into N bins randomly one by one, each bin can have any number of balls, then in average how many bins have only one ball?

Since N bins have no difference, we first consider the probability that only one ball falls in a given bin. There are N^K possible ways to put K balls into N bins. We can divide the procedure into two steps to consider the possibility of only one ball in a given bin. At first, we pick one from the K balls into this bin, there are C_K^1 possibilities. Then we put the rest $K-1$ balls into the rest $N-1$ bins, there are $(N-1)^{K-1}$ possibilities. Using the multiplication principle, there are totally $C_K^1(N-1)^{K-1}$ possibilities, so that the probability that only one ball falls in the given bin is $\frac{C_K^1(N-1)^{K-1}}{N^K}$. Since there are N bins, the average number of the bins that have only one ball is

$$N\frac{C_K^1(N-1)^{K-1}}{N^K} = K\left(\frac{N-1}{N}\right)^{K-1}. \tag{29}$$

The pulse collision problem is the same as the balls-bins problem. Since the pulse arrives randomly at uniform and discrete intervals, and there are N time slots and K arrival pulses, the average number of pulses that do not collide is (29), therefore the collision probability is (28). Without collision, the network throughput can increase with the number of cooperative nodes. However, the collision probability will also increase with the node number.

In MA modes, since the received signal power and interference power are different for each user, the achievable rate is also different even given the same required β^*. The throughtput of MA mode is

$$R_{t,\mathrm{MA}} = \sum_{k=1}^{K} R_{b,k}(1-p_c). \tag{30}$$

Like in BC modes, we want to see the balance of increased communication links and the increased collision probability in terms of K, thus we consider a special case that each link has the same data rate and $R_b = R_f$, then $N = 1/(R_bT_p)$ and the collision probability

$$p_c = 1 - (1 - R_bT_p)^{K-1}. \tag{31}$$

The throughput of MA mode becomes

$$R_{t,\mathrm{MA}} = KR_b(1-R_bT_p)^{K-1}. \tag{32}$$

We will see the impact of K in next section.

V. NUMERICAL RESULTS

In this section, we will compare the throughput of the cooperative relay network using three kinds of prefilters, analyze the optimal number of relay nodes and the impact of collision on the throughput through numerical results.

Observe (17), (20), and (23), we can see that the data rate in BC modes is independent of the received power if R_b is normalized by P_r/N_0. This normalized data rate only depends on the network load α and the required SINR, β^*. Fig. 2 shows the numerical results of the normalized throughput in BC modes, *i.e.*, $R_{t,\mathrm{BC}}/(P_r/N_0)$, versus the number of cooperative relay nodes K, where three kinds of prefilters are compared. The UWB pulse width T_p is assumed to be 1 ns, and the maximal channel delay $\tau_{\max}$ is 60 ns, such that the number of resolvable paths $L = 60$. For reliable communication, the required SINR β^* is assumed to be 4.2 dB.

It is shown from the figure that there is no big difference of the normalized throughputs of the network with different prefilters when the number of relay nodes is less than 5. The difference will increase when more nodes participate in relaying. As expected, the MMSE prefilter performs the best, TR prefilter performs the worst. The optimal relay numbers of the TR, ZF and MMSE prefiltering schemes are 11, 30 and 41, respectively. Using more relay nodes will reduce the throughput.

From (26) we know that, in MA modes the data rate of each user depends on the link distances and path losses of all users, thus it is hard to show all possible scenarios except for the equal distance case. It is shown from (32) that, when all the users have the same data rate, R_b, and the pulse width is given, the throughput, $R_{t,\mathrm{MA}}$, only depends on R_b and the relay node number K. The increasing of both R_b and K will increase the collision probability, although the single user data rate and the relay links will also increase. Fig. 3 shows the network throughput in MA mode versus the single user data rate and the relay number, where the pulse width is 1 ns. In the upper part of the figure, R_b is fixed as 50 Mbps, and in the lower part of the figure, K is fixed as 10. For comparison, the network throughput under the assumption of collision-free is also shown. We can see that the impact of collision becomes

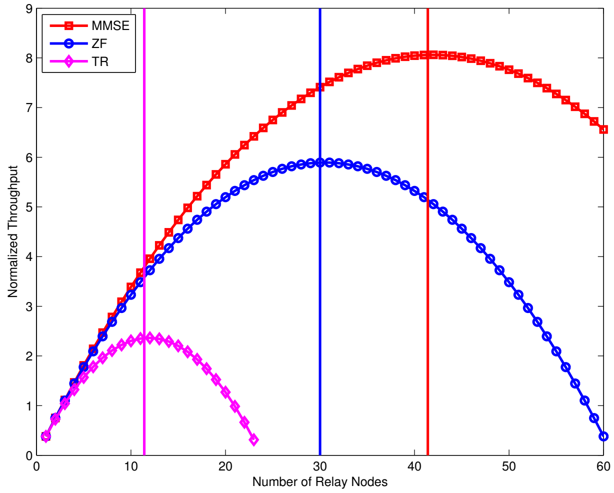

Fig. 2. Normalized throughput versus the number of cooperative relay nodes in BC modes, where $L = 60$, β^*=4.2 dB. The vertical lines indicate the optimal relay numbers.

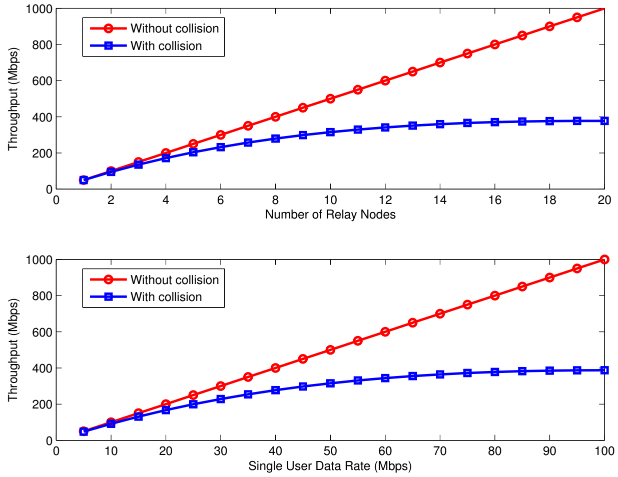

Fig. 3. Network throughput versus the number of cooperative relay nodes and single user data rate in MA modes, where $R_b = 50$ Mbps in the upper part and $K = 10$ in the lower part.

apparent when $K > 4$ in the upper case and $R_b > 20$ Mbps in the lower case.

VI. CONCLUSION

To apply UWB networks for long-distance high-rate transmission, a cooperative relay scheme using space-time focusing transmission is proposed in this paper. Theoretical analysis and numerical results on network throughput are provided, which indicate that there exists an optimal cooperative relay number to maximize the network throughput since more relay nodes will cause undesirable mutual interferences in BC modes and collisions in MA modes. The simple TR scheme only performs well in few relay nodes and low-rate scenarios while advanced prefiltering algorithms become superior when more nodes participate in cooperation and when date rate is high.

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